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Lead in ancient Rome's city waters

Hugo Delile^{a,b,1}, Janne Blichert-Toft^{b,c}, Jean-Philippe Goiran^d, Simon Keay^e, and Francis Albarède^{b,c}

^aUniversité Lumière Lyon 2, Centre National de la Recherche Scientifique-Unité Mixte de Recherche (CNRS UMR) 5600, 69676 Bron, France; ^bEcole Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, CNRS UMR 5276, 69007 Lyon, France; ^cDepartment of Earth Science, Rice University, Houston, TX 77005; ^dMaison de l'Orient et de la Méditerranée, CNRS UMR 5133, 69365 Lyon Cedex 7, France; and ^eArchaeology, Faculty of Humanities, University of Southampton, Southampton SO17 1BF, Great Britain

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It is now universally accepted that utilization of lead for domestic purposes and water distribution presents a major health hazard. The ancient Roman world was unaware of these risks. How far the gigantic network of lead pipes used in ancient Rome compromised public health in the city is unknown. Lead isotopes in sediments from the harbor of Imperial Rome register the presence of a strong anthropogenic component during the beginning of the Common Era and the Early Middle Ages. They demonstrate that the lead pipes of the water distribution system increased Pb contents in drinking water of the capital city by up to two orders of magnitude over the natural background. The Pb isotope record shows that the discontinuities in the pollution of the Tiber by lead are intimately entwined with the major issues affecting Late Antique Rome and its water distribution system.

harbor geoarchaeology | paleopollution | Late Holocene | ore provenance | sedimentology

Statistics on demography, money supply and metal circulation, life and health standards, and many other social parameters required to understand modern history are largely missing from the written record of the ancient past. For example, the apparently simple question of how the population of ancient Rome evolved is still unresolved (1, 2), prompting the design of indirect estimates (3). Another well-publicized problem illustrating the lack of primary sources of accurate information is the decade-old debate on Pb poisoning of the high society of Rome, either by lead water pipes or grape juice concoctions prepared in lead cups (4–9). Here we focus on the condition of Pb in the public waters of ancient Rome. Lead is regarded as a powerful and ubiquitous indicator of the manufacturing status of a society. For example, a surge in Pb concentrations in the Greenland ice-core record was correlated with the height of the Roman Empire (10). Three out of the four existing Pb isotopes are rapidly modified by the radioactive decay of natural uranium or thorium over geological time. The mining of ores from geologically diverse areas produces metallic Pb with variable isotopic abundances that depend on the tectonic age and the Th/U and U/Pb ratios of the mining district. Archaeologists interested in the provenance of artifacts routinely tap this wealth of information (11). To explore how the supply of metals from all over the Roman world and their utilization may have affected the nearby environment of ancient Rome, the present work sets out to investigate the isotope compositions of Pb in sediment cores from the Trajanic harbor basin at Portus, the maritime port of Imperial Rome, and the channel connecting Portus with the Tiber (Canale Romano) (Fig. S1). Harbors are excellent sedimentary traps. The record of human Pb pollution from the time that the harbor basin was excavated (ca. 112 AD) and well into the Middle Ages offers a new historical, ca. 1,000 y-long perspective on the evolution of Pb released by Rome, its water distribution system, and the major disruptive events that affected the life of the capital city and its harbor.

In 42 AD Claudius started the construction of an open coastal port to compensate for the long-standing shortcomings of the existing system for supplying Rome from the Mediterranean,

notably the small scale of the harbor and anchorage facilities at Ostia and the long route of communication with the principal maritime port at Puteoli (Pozzuoli) on the Bay of Naples (12). The inland ~0.4 km² Trajanic basin, which was excavated in the early years of the second century AD in response to the growing demands of an expanding population in Rome, offered both safe mooring to sea-going merchant ships and immense warehouses and other buildings (13–15). Communication between the Claudian and Trajanic basins was facilitated by an entrance channel, into which the ca. 9-m-long core TR14 was drilled. Up until the Middle Ages, the Trajanic basin was also accessed from a man-made branch of the Tiber (Fossa Traiana; what is now the Fiumicino Canal) by means of the Canale Traverso. The transport of sand and silt sediments from this channel to the Trajanic Harbor has been attested to by sedimentological, geochemical, and ostracod analyses (16–18). The now filled-in Canale Romano, which ran past the southwestern side of the Trajanic basin toward the Tiber, was used to carry cargoes transshipped on to river-going craft bound for Rome (15). A 13-m-long core labeled CN1 was drilled into the sediments of the Canale Romano. The detailed sedimentology and geochemistry of core TR14 are given elsewhere together with ¹⁴C ages (18). Some ¹⁴C dates likewise were obtained for core CN1 (Table S1). For reference and modeling purposes, the bedload of the modern Tiber between Rome and the Tiber delta was also sampled (Table S2), as were five different Roman Pb water pipes (*fistulae*) collected in Rome and dating to between the first and the second centuries AD (Fig. S2). In all, 42 samples from TR14, 37 samples from CN1, 6 samples from the Tiber bedload, and 10 samples from the five Roman *fistulae* were measured for their Pb isotope compositions at the Ecole Normale Supérieure de Lyon.

Significance

Thirty years ago, Jerome Nriagu argued in a milestone paper that Roman civilization collapsed as a result of lead poisoning. Clair Patterson, the scientist who convinced governments to ban lead from gasoline, enthusiastically endorsed this idea, which nevertheless triggered a volley of publications aimed at refuting it. Although today lead is no longer seen as the prime culprit of Rome's demise, its status in the system of water distribution by lead pipes (*fistulae*) still stands as a major public health issue. By measuring Pb isotope compositions of sediments from the Tiber River and the Trajanic Harbor, the present work shows that "tap water" from ancient Rome had 100 times more lead than local spring waters.

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¹To whom correspondence should be addressed. E-mail: hdelile@gmail.com.

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Results and Discussion

The TR14 core can be broken down into successive sedimentary units corresponding to different time slices: (i) preharbor up to *ca.* 100 AD, (ii) Early Empire up to *ca.* 250 AD, (iii) Late Empire up to *ca.* 500 AD, (iv) Early Middle Ages up to *ca.* 800 AD, and (v) Late Middle Ages (see the “Historical period age-depth model” columns in Fig. 1). Age boundaries between units may be uncertain by up to 100 y. Silts and sands dominate sediment mineralogy. The preharbor sequence attests to deposition in an environment of deltaic progradation (19). The construction of the harbor brings about a sharp sedimentological change and marks the beginning of the harbor mud deposits. A well-

stratified ~50-cm-thick layer within the Early Empire deposits (753 cm) displaying well-preserved shells does not appear in other cores and may signal local dredging (18, 20). The layer corresponding to the Early Middle Ages contains more carbonates and ostracods of brackish affinity than the rest of the core. At the top, the sediments from the Late Middle Ages horizon are characteristic of flood plain deposits (17, 18).

In Fig. 1, two different representations of lead isotope variations in TR14 and CN1 have been used: First (Fig. 1A), the conventional raw isotopic ratios in which ^{206}Pb is kept as the denominator; and, second (Fig. 1B), a derived set of geologically informed parameters which will now be explained. In compliance

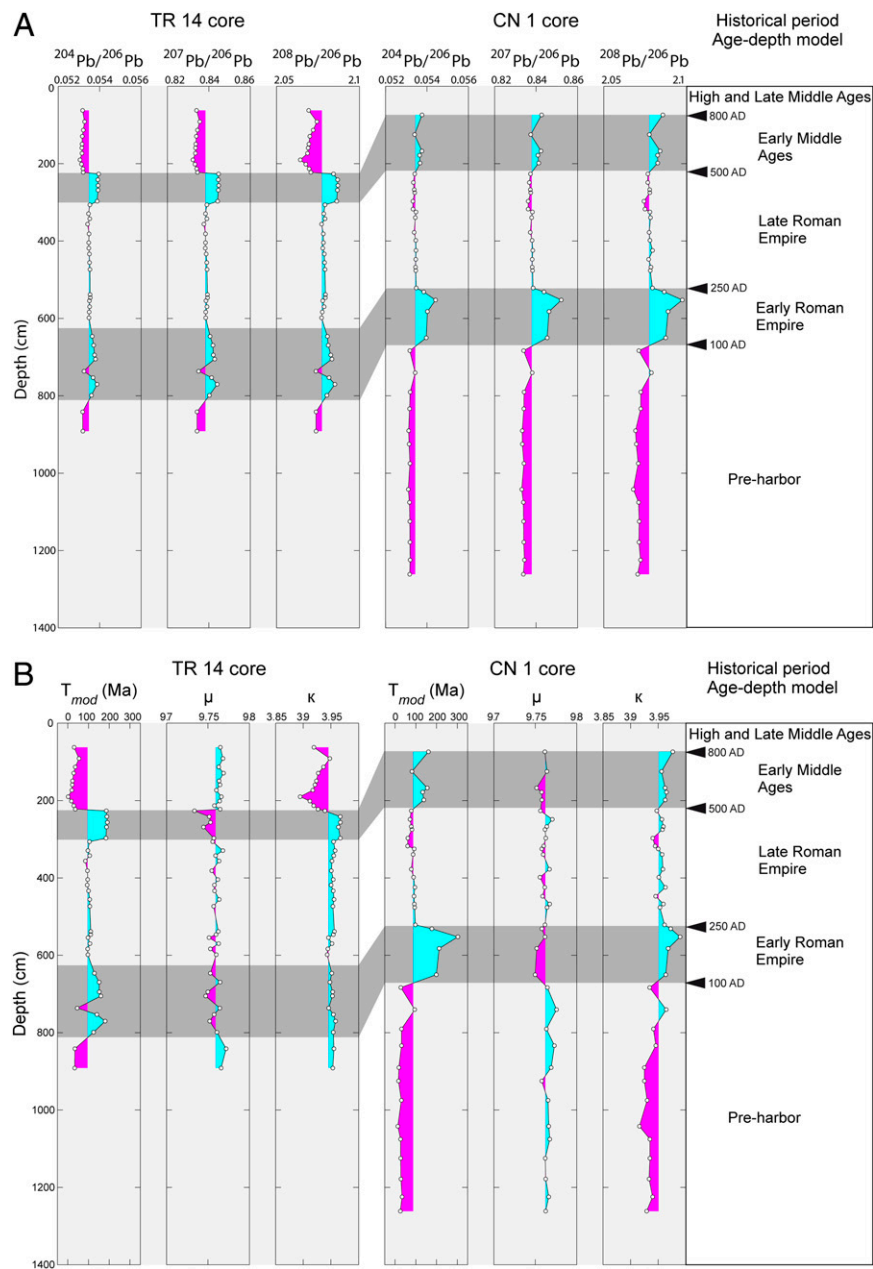
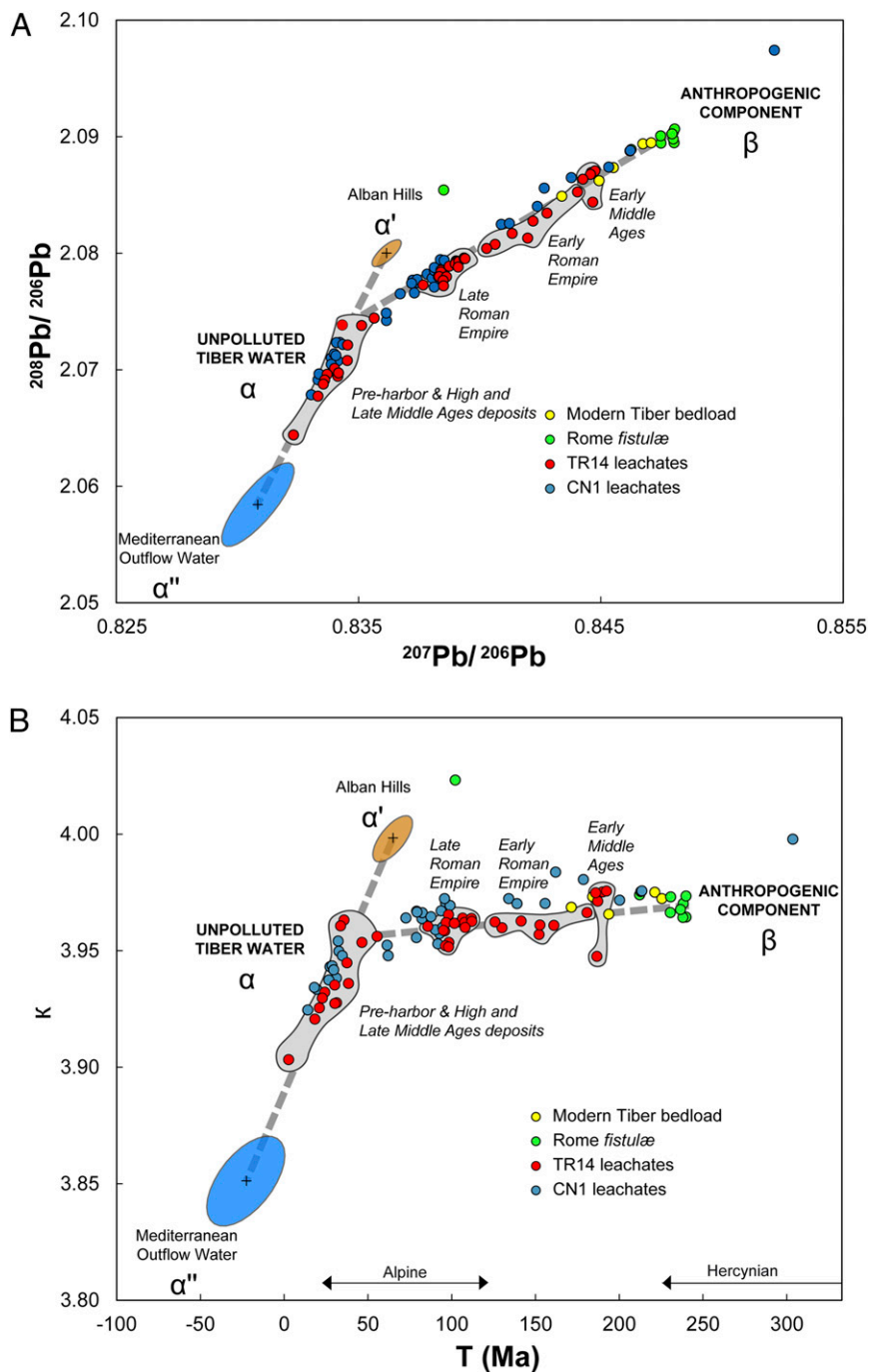


Fig. 1. Chronostratigraphic evolution of (A) the raw isotopic ratios of the cores TR14 and CN1 and (B) the geological parameters T_{mod} , $^{238}\text{U}/^{204}\text{Pb}$ (μ), and $^{232}\text{Th}/^{238}\text{U}$ (κ) derived from the raw isotope ratios as described in the main text. The different time slice boundaries (indicated with black arrowheads and highlighted by alternating light and dark gray shading for better visibility) derived from the age-depth model of core TR14 (18) coincide with major Pb isotope compositional shifts prominent in both cores. Hercynian Pb shows up during the Early Roman Empire and Early Middle Ages. In contrast, low-Th/U natural Pb dominates both the preharbor sequence and the flood plain deposits at the top of TR14.



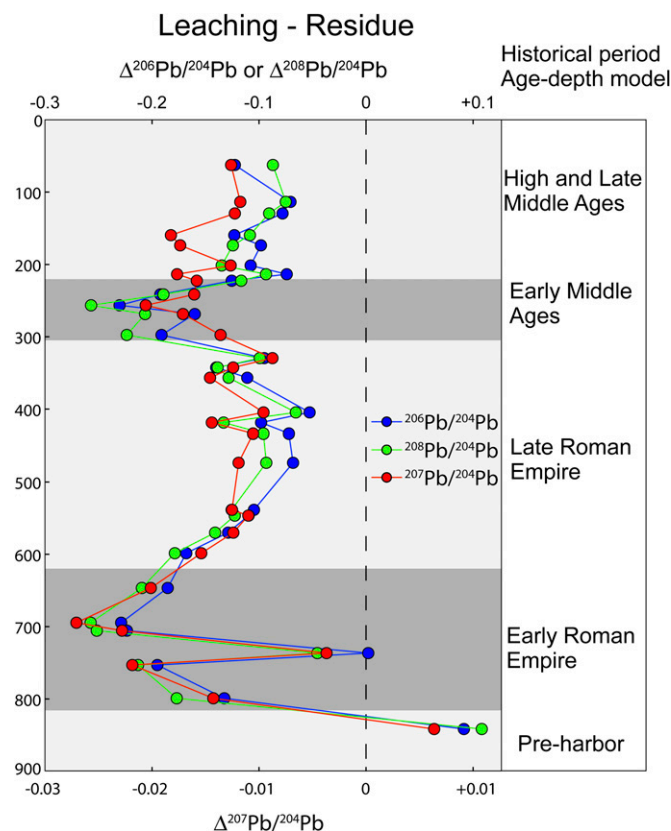


Fig. 4. TR14 downcore behavior of the isotopic contrast (Δ Pb isotope ratios) between the residue and the leachate. Increasing distance from the zero dashed line (left side of the figure) indicates increasingly predominant anthropogenic impact, which is strongest during the Early Roman Empire and the Early Middle Ages. Time slice model as in Fig. 1.

natural origin (trend $\alpha' - \alpha''$). Excavation of basin deposits dating to the period of the Early Roman Empire coincides with both a surge of Hercynian Pb in leachates and a dramatic drop in the isotopic contrast between the residue and the leachate (trend $\alpha - \beta$) (Fig. 4). At this time, the Roman Empire reached the height of its conquests, especially in western European territories such as Britain (Fig. S3). The isotopic contrast between the fractions rapidly diminishes, although quite smoothly, from the Early to the Late Roman Imperial periods. This change is largely accounted for by the dramatically smaller contribution of anthropogenic Pb to leachates and therefore by a lesser pollution of Tiber water. One interpretation of this may be a redirection of spring water away from the lead pipes of Rome, in some way related to the controversial decline of the population (3, 37) or to a poorly documented deterioration of the water distribution system.

At the end of the Late Roman Empire and throughout the Early Middle Ages section of TR14, the isotopic difference between the leachate and the residue bounces back and the presence of a rather homogenous anthropogenic component rich in Hercynian Pb again becomes prevalent in leachates (Figs. 2 and 4). The discontinuity appears in both the TR14 and CN1 cores (Fig. 1). The end of the Early Middle Ages section (~ 800 AD) is also brutal and signals the return of uncontaminated Pb in the Tiber (trend $\alpha' - \alpha''$). The persistence of Hercynian Pb in the bedload of the modern Tiber nevertheless indicates that centuries of contamination, possibly in the form of Pb carbonates, left a lasting imprint on the river sediments.

The consistency of the Pb isotope results from the CN1 core, which is expected to carry a straightforward Tiber signal, with those from the TR14 core is rather good despite the latter being

susceptible to both harbor activity and input of water from the Portus aqueduct, which has its source in the vicinity of modern Ponte Galeria. Both cores reflect the presence of a Hercynian end-member and coincide on the timing of major isotopic shifts. κ values in the CN1 core may, however, be marginally higher than those in TR14, especially during the Early Empire. It is unfortunate that the Pb isotope database on pipes used for water distribution is still too limited to identify such small differences with confidence.

The extensive nature of the harbor installations calls for additional work beyond the 95 samples of sediment core, bedload, and Pb pipes from Portus and the Tiber analyzed in this study to demonstrate unambiguously that the observed discontinuities in the Pb isotope and overall geochemical record correspond to catastrophic disruptions of Portus activity. Although the coastal position of the port leaves the Trajanic basin vulnerable to river vagaries and maritime hazards, the lack of coarse gravels and sediment sorting, combined with the good preservation of the delicate ostracod shells, are strong evidence against exceptional floods, storms, and tsunamis. The age-depth model (18) is certainly evocative of some critical dates of Roman history. As speculated by Delile et al. (18) based on the ^{14}C record of TR14 and adjacent cores, transitions between units may be correlated with the initial excavation of the Trajanic basin (by *ca.* 112 AD), the continued use of the port during the third century (*ca.* 250 AD), the gradual fortification and contraction of the port in the later fifth and earlier sixth centuries (*ca.* 500 AD), and the transition to the post-Byzantine period. The later fifth and sixth century transition is coeval with Belisarius' fixing of the decommissioned aqueducts of Rome (38) at the end of the Gothic Wars (535–554 AD). Byzantine repairs of the water distribution system may have remobilized massive amounts of corrosion products from abandoned lead pipes in which water may have stagnated for protracted lengths of time. Although a causal relationship cannot be formally demonstrated, the discontinuities in the cores at Portus seem contemporaneous with historically documented events such as the struggle for the control of the port between Gothic and Byzantine forces (536–552 AD) and the damages inflicted to the water distribution system during the Arab sack of Rome in the mid-ninth century. Further work is needed to learn whether the causes of Portus' demise were natural, with the harbor finally falling into disuse on account of flood plain deposits, possibly after the major floods of 856 AD (39–41), or a consequence of military events (39).

Conclusions

This work has shown that the labile fraction of sediments from Portus and the Tiber bedload attests to pervasive Pb contamination of river water by the Pb plumbing controlling water distribution in Rome. Lead pollution of "tap water" in Roman times is clearly measurable, but unlikely to have been truly harmful. The discontinuities punctuating the Pb isotope record provide a strong background against which ideas about the changing character of the port can be tested.

Materials and Methods

After removal of the coarse gravel fraction, 500 mg of sample were crushed and treated with chloroform to remove most of the abundant organic fraction. The residue was rinsed and leached in dilute HBr. Because lead pipe corrosion products, such as Pb carbonates (42, 43), were suspected to be present in the sediments and carry a signal from aqueducts, no attempt was made at using the more specific protocols developed to selectively extract hydroxide coatings (e.g., ref. 44). Lead from the leachates was purified on an ion exchange resin using HBr as eluent of the sample matrix and HCl to elute Pb. The amounts of Pb extracted were large (>1 μg) and orders of magnitude above the blank of the procedure (~ 20 μg). Lead isotope compositions were analyzed by multicollector inductively-coupled plasma mass spectrometry on both the residues and the leachates of the samples from TR14 and the results were so systematic that no further attempt was made to also measure the residues from CN1 (Table S2).

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